

# Bringing VY Canis Majoris Down to Size: An Improved Determination of Its Effective Temperature

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## ABSTRACT

The star VY CMa is a late-type M supergiant with many peculiarities, mostly related to the intense circumstellar environment due to the star's high mass-loss rate. Claims have been made that would suggest this star is considerably more luminous ( $L \sim 5 \times 10^5 L_\odot$ ) and larger ( $R \sim 2800 R_\odot$ ) than other Galactic red supergiants (RSGs). Indeed, such a location in the H-R diagram would be well in the “Hayashi forbidden zone” where stars cannot be in hydrostatic equilibrium. These extraordinary properties, however, rest upon an assumed effective temperature of 2800-3000 K, far cooler than recent work have shown RSGs to be. To obtain a better estimate, we fit newly obtained spectrophotometry in the optical and NIR with the same MARCS models used for our recent determination of the physical properties of other RSGs; we also use  $V - K$  and  $V - J$  from the literature to derive an effective temperatures. We find that the star likely has a temperature of 3650 K, a luminosity  $L \sim 6 \times 10^4 L_\odot$ , and a radius of  $\sim 600 R_\odot$ . These values are consistent with VY CMa being an ordinary evolved  $15 M_\odot$  RSG, and agree well with the Geneva evolutionary tracks. We find that the circumstellar dust region has a temperature of 760 K, and an effective radius  $\sim 130$  AU, if spherical geometry is assumed for the latter. What causes this star to have such a high mass-loss, and large variations in brightness (but with little change in color), remains a mystery at present, although we speculate that perhaps this star (and NML Cyg) are simply normal RSGs caught during an unusually unstable time.

*Subject headings:* stars: late-type—stars: evolution—stars: mass loss—supergiants

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## 1. Introduction

VY CMa is a late-type M supergiant that is remarkable in many ways. It has a large IR excess, making it one of the brightest objects in the sky at  $5\text{--}20\mu\text{m}$ , indicative of a dust shell (or disk) heated by the star (Herbig 1970a). The inferred mass-loss rate is huge for a red supergiant (RSG), about  $2 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$  (Danchi et al. 1994). Like other late-type mass-losing stars, it has strong molecular maser emission; in fact, it was one of the first radio masers discovered (Wilson & Barrett 1967; Eliasson & Bartlett 1969). The star is embedded in an asymmetric dust reflection nebula which extends  $8\text{--}10''$  from the star, which is highly structured (Monnier et al. 1999; Smith et al. 2001; Humphreys et al. 2005). This nebula is so bright that it was discovered in 1917 with an 18-cm telescope, but was somehow missed by earlier observers with much better equipment, leading to the speculation that the nebula is only 100 years old (Herbig 1972, Worley 1972). The photometric history of the star extends back to 1801, and shows the star fading visually by 2 mag since that time (Robinson 1971), with typical variations of  $\pm 2$  mag (Robinson 1970, Henden 2006), but with little change in color.

Spectroscopically, the star is unusual in two regards. First, although careful long-term monitoring by Wallerstein (1958, 1977; Wallerstein & Gonzalez 2001) has shown that the overall spectrum has stayed constant at M3-M5 I for over 40 years, the spectrum shows emission of low-excitation lines, including Na I and K I, as well as emission in the band heads of TiO and ScO (Wallerstein 1958; Herbig 1970b), which do change over the time scales of months. Secondly, the star’s spectrum has been described as “veiled” (Herbig 1970b, Humphreys 1974), a term used to denote the general washing out of absorption features seen in the spectra of some Mira variables (Merrill et al. 1962) and other luminous RSGs (Humphreys & Lockwood 1972).

However, our interest in VY CMa was prompted by the extraordinary physical properties often assumed for this star (Le Sidaner & Le Bertre 1996, Smith et al. 2001; Monnier et al. 2004; Humphreys et al. 2005), such as a radius of  $1800\text{--}3000 R_{\odot}$  ( $8.3\text{--}14$  AU), significantly larger than  $\sim 1500 R_{\odot}$  value measured for the three largest RSGs in a sample of 74 Galactic stars we have recently analyzed (Levesque et al. 2005, hereafter Paper I). The corresponding luminosity ( $2\text{--}5 \times 10^5 L_{\odot}$ , or  $M_{\text{bol}} = -8.5$  to  $-9.5$ ) is near or beyond the highest luminosities of other known RSGs (Paper I). Usually such problems can be traced to an uncertainty in the distance, but in the case of VY CMa the distance is relatively well determined, as the star is associated with a molecular cloud at a distance of 1.5 kpc (Lada & Reid 1978). This distance is consistent with the proper motions measured from  $\text{H}_2\text{O}$  maser features (Richards et al. 1998). Furthermore, the very large diameter appears to be supported by direct interferometry (Monnier et al. 2004).

The extreme properties determined for this star rest primarily upon the assumed effective temperature of 2800 K, a value which comes from Le Sidaner & Le Bertre (1996) who *adopted* this temperature based upon the star’s spectral type<sup>1</sup>. Were the star at 2800 K with  $M_{\text{bol}} \sim -9$  it would be considerably cooler and more luminous than current evolutionary models allow, and would be located in the “forbidden zone” to the right of the Hayashi track<sup>2</sup> (Fig. 1). Oddly, no previous authors have commented on this fact. Such objects are not in hydrostatic equilibrium. Although RSGs would not be found in this region, collapsing protostars might, and indeed Wallerstein (1978) and Herbig (1970b) have long argued that VY CMa might be a recently-formed object rather than an evolved massive star, although based upon other reasoning.

Understanding the nature of this interesting object rests upon knowing its effective temperature, as this is also key to determining the star’s bolometric luminosity. We have recently used MARCS model atmospheres (Gustafsson et al. 1975, Plez et al. 1992, Plez 2003, Gustafsson et al. 2003) to derive the physical properties of Galactic and Magellanic Cloud RSGs. Here we apply the same techniques to VY CMa, using newly acquired optical/NIR spectrophotometry and existing IR photometry. Thermal emission from the dust apparently begins to dominate the spectral energy distribution past  $2\mu$  (see Fig. 1 of Hyland et al. 1969), and thus we expect that the use of  $V - K$  will lead to too low an effective temperature. However, scattering by the dust in the optical/NIR region may partially fill in spectral absorption features (i.e., veiling), and fitting the molecular bands using the MARCS models may lead to too high an effective temperature. The true effective temperature of the star should be between these limits, and using  $V - J$  may help determine which is closer.

## 2. Determination of Physical Properties

We observed VY CMa using the CTIO 4-m telescope and RC spectrograph (Loral CCD in blue air Schmidt camera) in the red (5300Å-9000Å) using a 2 sec exposure on 20 Dec 2005,

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<sup>1</sup>Le Sidaner & Le Bertre (1996) cite the effective temperature scale of Dyck et al. (1974), but 2800 K is much cooler than what Dyck et al. (1974) adopt for an M4 star—roughly 3400 K; see their Fig. 7.

<sup>2</sup>Note that the Hayashi tracks are analytically of the form  $\log T_{\text{eff}} = 0.02M_{\text{bol}} + 0.2 \log M + C$  (Kippenhahn & Weigert 1990; Bohm-Vitense 1992). For RSGs,  $\log M = 0.5 - 0.10M_{\text{bol}}$  (Paper I), and hence the edge of the forbidden zone must correspond roughly to a constant temperature for massive stars. The exact value of this temperature depends critically upon the treatment of convection; here we adopt  $\log T_{\text{eff}} = 3.55$ , where we have shifted the results of Ezer & Cameron (1967) by  $-0.05$  dex (consistent with a slight lowering of their adopted value of  $l/H_P$  from 2) in order to give a better match to the evolutionary tracks of Meynet & Maeder (2005). See also Henyey et al. (1965), and discussion in Kippenhahn & Weigert (1990).

and in the blue (3400Å-6200Å) using a 30 sec exposure on 21 Dec 2005. For both setups we used grating KPGL2 (316 l mm<sup>-1</sup>). The dispersion was 2 Å pixel<sup>-1</sup>, and we achieved a spectral resolution of 7.5 Å (3.8 pixels) using a 225μm slit (1.5"). For the red observations we used an WG-495 filter to block out 2nd order blue light. For the blue observations, we used a BG-39 filter to remove any possibility of scattered red light affecting our observations, especially in the far blue and near UV where the stellar flux is small (see Massey et al. 2005; Levesque et al. 2006, hereafter, Paper II). The spectrograph was rotated to the parallactic angle for each observation. Multiple observations of spectrophotometric flux standards were obtained throughout the night, and the agreement between these standards was typically 1-2% after a grey shift. Observations of several “featureless” stars allowed us to remove the telluric absorption to first order, following Bessell (1999). The data were flat-fielded using projector flat data obtained during the day, and were wavelength calibrated using exposures of a He-Ne-Ar comparison arc obtained immediately before (blue) or after (red) the exposure of VY CMa. Finally, the reduced blue and red spectra were combined with a small adjustment to bring the flux levels in the overlap region into agreement. We show the spectrum of VY CMa in Fig. 2a, along with line identifications.

The spectra were fit using the same MARCS stellar atmosphere models used in Paper I, using a similar technique. We compared the synthetic spectra to the observed one, matching the line depths of the molecular bands (primarily TiO) and adjusting the reddening of the model with a Cardelli et al. (1989) law ( $R_V = 3.1$ ). A satisfactory fit was quickly obtained with a  $T_{\text{eff}}=3650$  K model, and  $A_V = 3.20$  (Fig. 2b, red curve). Our estimate on the uncertainties are 25 K for  $T_{\text{eff}}$  and 0.15 on  $A_V$ . This reddening is in good agreement with the  $E(B - V) \sim 1$  value suggested by Wallerstein & Gonzalez (2001). We used a  $\log g = 0.0$  model for the fitting; a model with  $\log g = +0.5$  gives a better fit to the gentle red slopes of some of the TiO bands in the NIR, but  $\log g = 0.0$  is more consistent with the star’s inferred physical properties. Use of the higher surface gravity model would increase the reddening negligibly, and not change the temperature. The discrepancy in the UV between the observed and expected fluxes is similar to that seen around other RSGs with large amounts of circumstellar dust, as inferred by excess reddening (Massey et al. 2005), and is likely due to scattering of light from the star by the dust, possibly combined with a distribution of grain sizes that is larger than normal.

We list the star’s derived physical properties in Table 1. For this, we adopted  $V = 8.5$ , a value close the star’s average brightness, and similar to the value the star had at the time we observed it spectroscopically, according to estimates by the AAVSO (Henden 2006, see below). With a distance of 1.5 kpc, and our values for  $A_V$ , this determines the absolute visual magnitude ( $M_V$ ). The MARCS models provide the bolometric corrections as a function of effective temperature (see Paper I), allowing us to determine the star’s bolometric luminosity

$L$ . The effective stellar radius  $R$  then follows from  $L = 4\pi\sigma T_{\text{eff}}^4 R^2$ .

Although the temperature is *significantly* higher than that adopted by other workers, it is in accord with our own recent estimates of the effective temperature scale of RSGs (Paper I), corresponding to a type somewhat later than M2 I. Although the star’s spectrum has been variously described as M3-M4 I (Joy 1942), M5 I (Wallerstein 1958), and M4-M5 I (Humphreys 1974), we would actually classify it as M2.5 I, based upon the TiO bands we normally use, i.e.,  $\lambda 6158$ ,  $\lambda 6658$ , and  $\lambda 7054$  (see also Jaschek & Jaschek 1990). However, our results are not really in conflict with earlier studies, which based their classifications primarily on blue (photographic) spectrograms. If instead we had used TiO bands further to the blue (such as  $\lambda 4761$ ,  $\lambda 4954$ ,  $\lambda 5167$ , and  $\lambda 5448$ ) we would in fact have arrived at an M4 I classification (Fig. 2a). We did a fit based upon these TiO bands, and found  $T_{\text{eff}}=3450$  K and a lower reddening ( $A_V = 2.00$ ). One can argue that the TiO bands in the blue are less likely to be affected by veiling (Humphreys 1974), but alternatively there is clearly excess flux in the blue due to dust scattering (Massey et al. 2005). In any event our fit to the TiO bands in the blue was considerably poorer compared to the overall spectrum (Fig. 2 b, purple curve), and so we are inclined to place more credence in the NIR fit. We include the derived physical parameters from the blue fit in Table I for comparison.

We can also estimate the star’s effective temperature using the star’s  $V - K$  color. There are two difficulties with this. The first is that the star is a notorious variable (Robinson 1970, 1971). In Fig. 3 we show the variations in the visual brightness of the star collected by the AAVSO over the years (Henden 2006), along with any published photoelectric  $V$  values. Oddly, the star has stayed remarkably constant in color during these shifts; for instance, the star faded by 0.4 mag in  $V$  during the photoelectric monitoring by Cousins & Lagerweij (1971), but remained essentially constant in  $B - V$  and  $U - B^3$ . There are two IR measurements in the literature:  $K = -0.62$  by Hyland et al. (1969) from November 1968, and  $K = +0.34$  (after transformation to the standard system of Bessel & Brett 1988, following Carpenter 2001) from 1999 November. Despite the 0.9 mag difference, the  $J - H$  and  $J - K$  colors are nearly identical:  $J - H = 1.49 \pm 0.10$  vs.  $1.35 \pm 0.47$  and  $J - K = 2.63 \pm 0.2$  vs.  $2.26 \pm 0.50$ , where the large errors correspond to the 2MASS colors, and are due to the photometry being derived from fitting the wings of the stellar profile<sup>4</sup>. More remarkably, if we take the  $V = 7.44$  magnitude reported by Hyland et al. (1969), (which is presumably contemporaneous with their  $K$  value) and the  $V = 8.40$  magnitude that corresponds to

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<sup>3</sup>Note that this conclusion differs from that of Robinson (1970), who finds that the star reddens as it fades.

<sup>4</sup>See [http://www.astro.virginia.edu/~mfs4n/2mass/allsky/bs\\_allsky.html](http://www.astro.virginia.edu/~mfs4n/2mass/allsky/bs_allsky.html).

the average of the AAVSO estimates near the time of the 2MASS observation, we find fortuitously identical colors,  $V - K = 8.06$ . We can deredden this using  $A_V = 3.20$  and  $A_K = 0.35$ , where we have assumed that  $A_K = 0.11A_V$ , following Schlegel et al. (1998), and obtain  $(V - K)_0 = 5.21$ . Using our calibration from Paper I, this corresponds to an effective temperature of  $T_{\text{eff}} = 3475$  K. An uncertainty of 0.2 mag in the color (not unreasonable) would correspond to an error in the temperature of 35 K. We include in Table 1 the physical parameters derived from this value.

The second difficulty with using  $V - K$  to estimate the effective temperature of the star is that this will provide only a lower limit, given that thermal emission significantly contaminates the  $K$ -band (Hyland et al. 1969) photometry. A better estimate then might come from the  $V - J$  colors. For both the Hyland et al. (1969) and 2MASS data sets we obtain  $V - J = 5.43$  and  $V - J = 5.45$ , respectively. If we deredden these by  $A_V = 3.20$  and  $A_J = 0.28A_V = 0.90$  (again, following Schlegel et al. 1998), we obtain  $(V - J)_0 = 3.14$ . Using the MARCS models for Galactic metallicity, we find that we expect

$$T_{\text{eff}} = 7260.0 - 2073.74(V - J)_0 + 371.600(V - J)_0^2 - 22.802(V - J)_0^3$$

for  $\log g = 0.0$  and  $4300 \geq T_{\text{eff}} \geq 3000$ . Thus, for VY CMa, the  $V - J$  colors imply a temperature of 3705 K. An uncertainty of 0.2 mag corresponds to an error of 90 K. This is in good agreement with the 3650 K temperature we obtained from fitting the red/NIR TiO bands.

How reliable are the temperatures derived from the MARCS models? In Paper I we showed that the temperatures and luminosities derived using these models brought Galactic RSGs into accordance with the predictions of modern stellar evolutionary theory; in Paper II we showed that this was also true at the lower metallicities of the LMC and SMC. We consider it unlikely that this agreement is coincidental, and instead believe this finding provides a powerful endorsement of each. Further, we have now shown (Paper II) that the MARCS models are self-consistent in that the temperatures derived from broad-band  $(V - R)_0$  are similar (to 30 K) with those derived from fitting the TiO lines. We do find (Paper II) that the broad-band  $(V - K)_0$  colors of the models yield effective temperatures that are  $\sim 100$  K warmer than those derived by the other means. We attribute this to the limitations of static 1D models, as spectra of RSGs in the optical and IR may reflect different atmospheric conditions due to the large surface granulation present in these stars.

### 3. Discussion

We have brought the same techniques to bear on VY CMa as we have on other RSGs. Contrary to previous claims, we find that its effective temperature is typical of RSGs (3450–3700 K) and that its luminosity, while high ( $M_{\text{bol}} = -7.0$  to  $-8.0$ , or  $L = 5 \times 10^4$  to  $1.3 \times 10^5 L_{\odot}$ ) is not extraordinary. Our preferred value comes from fitting the red/NIR TiO bands, which yield  $T_{\text{eff}}=3650$  K and  $M_{\text{bol}} = -7.2$  ( $L = 6.0 \times 10^4 L_{\odot}$ ); this is in good agreement with that found from the  $V - J$  photometry.

Monnier et al. (2004) used 2- $\mu\text{m}$  interferometry to obtain a diameter of VY CMa of 18.7 mas; at a distance of 1.5 kpc, this corresponds to a radius of  $3000 R_{\odot}$ , in seeming contradiction to the results obtained here. Adopting this large size leads to a temperature of 2700 K, in (un)fortuitous agreement with the value proposed by Le Sidaner & Le Bertre (1996). J. Monnier (private communication) was kind enough to offer two possible explanations. First, their analysis assumed that the dust shell did not have significant structure on the scale of the stellar diameter; if that were not the case, then the angular measurement might have included part of the dust shell. Secondly, it could be that VY CMa has a molecular water layer around the star that emits at  $2\mu\text{m}$ , similar to what is seen around some cool AGB stars. This would cause the continuum diameter to be larger than the photosphere. Higher resolution studies are now possible, and are being planned, to resolve this possible discrepancy.

Our improved estimate of the temperature of the star has little impact on the inferred properties of the circumstellar dust shell. If we adopt  $T_{\text{eff}}=3650$  K for the star, and assume that the  $J$ -band photometry is uncontaminated by the thermal emission (as is implied by the good agreement with the  $V - J$  colors and that found by fitting the red/NIR TiO bands), then we can compute both the temperature  $T_{\text{cs}}$  and effective area  $A_{\text{cs}}$  of the circumstellar material by comparing the dereddened IR colors with those of the stellar model. The dereddened 2MASS observations yield  $J_0 = 2.07$ ,  $H_0 = 1.03$ , and  $K_0 = -0.02$ . The colors corresponding to a MARCS  $T_{\text{eff}}=3650$  K,  $\log g = 0.0$  model are  $(J - H)_{\text{mod}} = 0.88$ ,  $(J - K)_{\text{mod}} = 1.11$ . We assume that the observed  $J_0$  is just the same as that of the model plus a normalization constant:  $J_0 = J_{\text{mod}} + C$ , but that the  $H_0$  and  $K_0$  contain a flux component due to the circumstellar shell ( $F_{\text{cs}}$ ):  $H_0 = -2.5 \log(F_{H*} + A_{\text{cs}}F_{H\text{cs}})$  (with a similar equation for  $K_0$ ), where  $A_{\text{cs}}$  is the emitting area of the circumstellar shell compared to that of the star, and  $F_{H*}$  is the flux from the star in  $H$ , namely  $10^{-(H_{\text{mod}}+C)/2.5}$ . Then it follows that  $A_{\text{cs}}F_{H\text{cs}}/F_{H*} = 10^{(H_{\text{mod}}+C-H_0)/2.5} - 1$ . We find that  $A_{\text{cs}}F_{H\text{cs}}/F_{H*} = 0.15$  and  $A_{\text{cs}}F_{K\text{cs}}/F_{K*} = 1.45$ . The ratio  $F_{K\text{cs}}/F_{H\text{cs}} = 9.6F_{K*}/F_{H*} = 11.9$ , which corresponds to a black-body temperature of 760 K. This is close to the 850 K temperature deduced from mid-IR photometry by Le Sidaner & Le Bertre (1996), given the uncertainties in  $JHK$ , and the small leverage we have

here compared to the mid-IR. It is also consistent with the temperature range estimated by Wallerstein (1958) for the low-excitation emission lines, and the 600 K excitation temperature estimated for the ScO emission by Herbig (1974). We can go one step further, however, and compute the area based upon the calculated fluxes per unit area of the MARCS model and a 760 K blackbody in the  $H$  and  $K$  bands. We find  $A_{\text{cs}} = 2130$  from  $H$ , and  $A_{\text{cs}} = 2155$  from  $K$ . Thus, the radius of the emitting region must be about 46 times that of the stellar radius, if it is a spherical surface. If the stellar radius is  $\sim 600R_{\odot}$ , this circumstellar material would have an effective radius  $\sim 130$  AU.

We find that the location of VY CMa in the HRD is consistent with that of an evolved  $15M_{\odot}$  star. Why then does VY CMa have so many peculiarities, as noted above? All of these phenomena (photometric fading by 2 mag over 2 centuries, “veiling” of the optical spectra, intense IR emission, low-excitation emission lines) are related to the rich circumstellar environment caused by the star’s very high mass-loss rate. We have recently shown (Massey et al. 2005) that in general the dust production rate of RSGs is proportional to the bolometric luminosity of the star, but Danchi et al. (1994) in particular has emphasized that the dust production is quite sporadic, with time scales on the order of a few decades. Could the mass-loss rates of RSGs vary so significantly that VY CMa is simply a normal RSG going through a short period of intense mass-loss that is normal? We have called attention here to a newly noted peculiarity, namely that the star’s brightness seems to change by large amounts with little change in colors—even the  $V - K$  colors. This is unlikely due to dust (due to the grayness), and suggests a luminosity change at nearly constant effective temperature. We note that since RSGs are fully convective, they do (by definition) lie on the edge of the Hayashi forbidden zone. If some instability caused the star to venture slightly into this zone, we would expect the star to undergo a very short, unstable period. We speculate that this might be responsible for variations in the star’s luminosity and in driving the dust production rate. Possibly VY CMa, and the more extreme IR object NML Cyg, are examples of normal RSGs that we have simply caught during an unusual time.

Our attention was originally called to this interesting star by John Monnier and Roberta Humphreys. We are also grateful for correspondence with George Herbig and George Wallerstein, whose seminal papers on this star made for interesting and enjoyable reading. We thank Knut Olsen for useful comments on the manuscript, and for his continued collaboration on the overall project of which this is a small part. This paper made use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. We acknowledge with thanks the variable star observations from the AAVSO International



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Table 1. Physical Properties VY CMa

Method	$T_{\text{eff}}$ (K)	$A_V$	$\log g[\text{cgs}]$	$M_V$	$M_{\text{bol}}$	$R/R_{\odot}$
TiO (red/NIR bands) <sup>a</sup>	$3650 \pm 25$	3.20	0.1	−5.6	−7.2	605
TiO (blue/yellow bands)	$3450 \pm 25$	2.00	0.1	−4.4	−6.9	595
V-K	$> 3475 \pm 35$	3.20 <sup>b</sup>	−0.2	−5.6 <sup>b</sup>	$> -8.0$	$< 955$
V-J	$3705 \pm 90$	3.20 <sup>b</sup>	0.2	−5.6 <sup>b</sup>	−7.0	545

<sup>a</sup>Preferred; see text.

<sup>b</sup>Adopted.

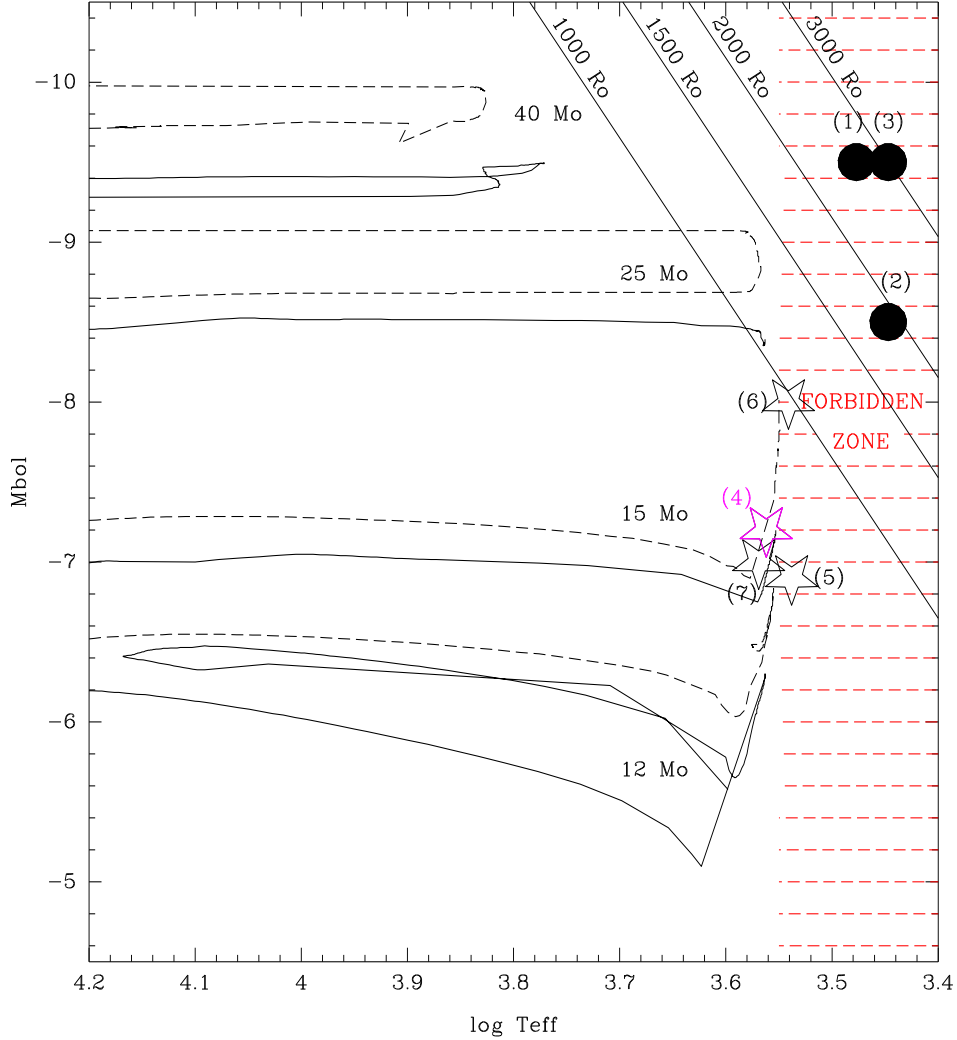


Fig. 1.— Location of VY CMa in the H-R Diagram. The three numbered filled circles correspond to the “old” parameters of VY CMa, where (1) is from Smith et al. (2001), (2) is from Monnier et al. (1999), and (3) is from Le Sidaner & Le Bertre (1996), where we have adjusted their luminosity to our adopted 1.5 kpc distance. In all three cases the effective temperature has simply been assumed based upon the spectral type. All three points lie well into the “forbidden zone” (hashed red area) to the right of the Hayashi limit, and so are hydrostatically unstable. The five-starred points correspond to the results of this paper: (4) is based on our solution fitting the NIR TiO bands; (5) is based upon our solution fitting the blue TiO bands; (6) is based upon the  $(V - K)_0$  photometry (and which we take to be a lower limit on the temperature, and an upper limit on the luminosity); and (7) is based upon the  $(V - J)_0$  colors. We denote our preferred values (point 4) in purple. The evolutionary tracks are from Meynet & Maeder (2005), with solid lines indicating no initial rotation, and dashed lines indicating the tracks with initial rotations of  $300 \text{ km s}^{-1}$ . The diagonal lines at upper right show lines of constant radii.

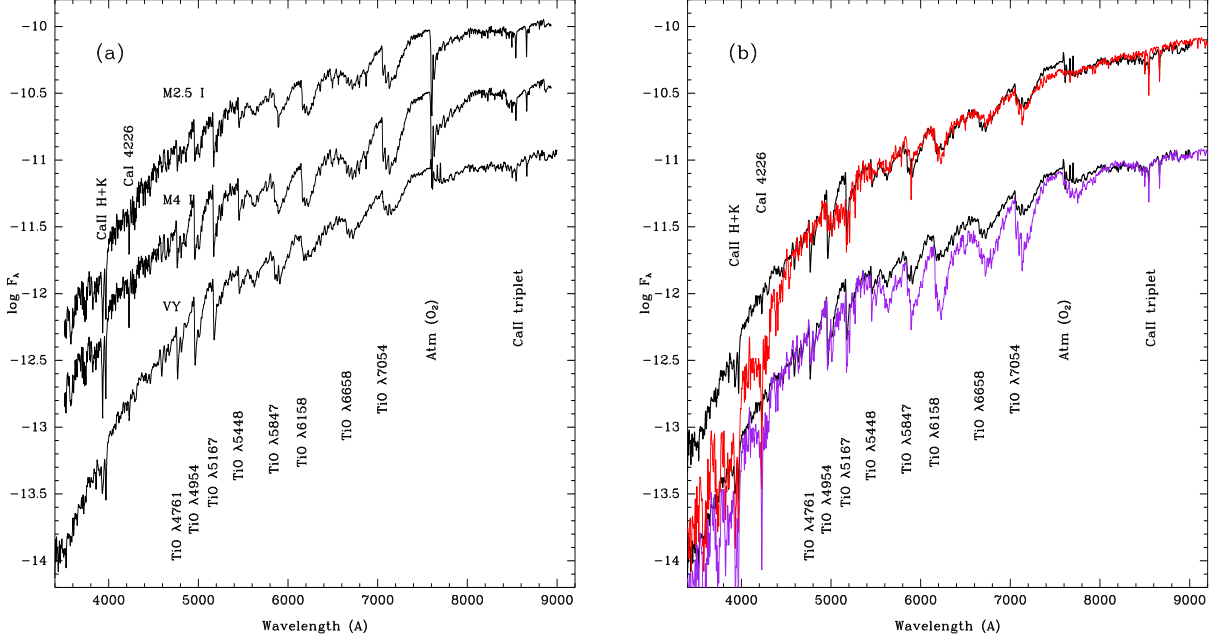


Fig. 2.— The spectrum of VY CMa. In (a) we compare the spectrum of VY CMa (bottom spectrum) to that of the M2 I star HD 100930 (top spectrum) and the M4 I star HD 93420 (middle spectrum), where the data for the two standards comes from Paper I, and have not been corrected for telluric features. The standards have been shifted vertically by arbitrary amounts. In (b) we show the model fits. The red curve is our preferred model fit ( $T_{\text{eff}}=3650$  K and  $A_V = 3.20$ ), which does a good job reproducing the TiO bands in the red (i.e., TiO  $\lambda\lambda$  6158, 6658, 7054), but produces TiO bands too weak in the blue (i.e., TiO  $\lambda\lambda$  4761, 4954, 5167). The spectrum (and model fit) have been shifted vertically. The lower spectrum shows the “fit” (purple) with a cooler model ( $T_{\text{eff}}=3450$  K and  $A_V = 2.00$ ). The TiO bands in the blue are in better agreement, but the model produces TiO bands that are much too strong in the red. As found for other RSGs with significant circumstellar dust, there is significant extra flux in the observed stellar continuum in the near-UV, due, we believe, to scattering by the dust (Massey et al. 2005). The models also do not do a good job of reproducing the atomic CaI and CaII features, as discussed in Paper I.

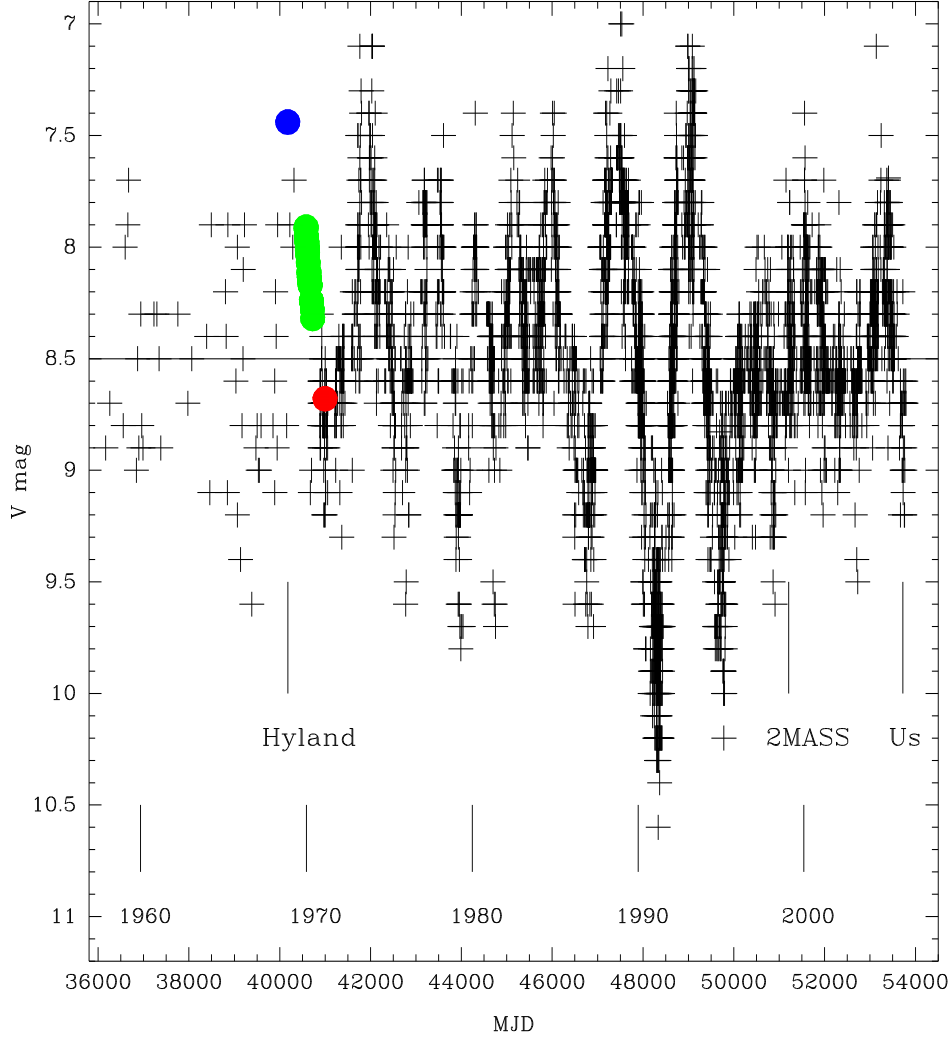


Fig. 3.— Visual photometry of VY CMa. The “+” symbols are visual estimates (typically  $\pm 0.2$  mag) from the AAVSO (Henden 2006). The colored filled circles are photoelectric  $V$  measurements: the blue point is that quoted by Hyland et al. (1969); the green points are from Cousins & Lagerweij (1971), and the red point is from that quoted by Wallerstein (1971). These indicate good agreement with the visual data. We indicate the times of the IR photometry (Hyland et al. (1969) and 2MASS) and of our spectrophotometry. The solid line at  $V = 8.5$  shows the median value throughout the AAVSO data set.